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Revolutionizing the Field of Green Chemistry: Exploiting the Potential of Magnetically Recoverable Nano-Catalysts

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ABSTRACT

Nowadays, most of the metallic zinc is produced through hydrometallurgical processes. To attain high-purity zinc through electrowinning, the concentration of chlorine ions in the electrolyte should not exceed 0.5 g/L due to its negative consequences. One in particular is the corrosion of non-consumable lead anodes, which is responsible for the dissolution of Pb that causes impurities in the produced zinc metal. Moreover, chlorine emission in the work environment could be a danger to the health of staff, which stems from the oxidation of chlorine ions on the non-consumable Pb anodes. In this research, a potential alternative procedure is employed to significantly reduce chlorine in zinc concentrate. The results showed that under the appropriate conditions of T=60 °C and 1 h of experiment, two-step dichlorination using water along with 20 g/L Na_2CO_3 had a salient efficiency of 98% and the lowest amount of 0.48 g/L chlorine remaining in the leaching solution. Compared to traditional dichlorination methods of zinc, the employed procedure had satisfying dichlorination efficiency, considering the economic aspects of the produced zinc, particularly on an industrial scale.

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1. Introduction to Chemistry and the Necessity of Sustainable Solutions

Green chemistry aims to develop sustainable and environmentally conscious chemical processes, an urgent need given mounting concerns about climate change and resource depletion [1,2]. Traditional methods often depend on chemicals that produce waste and use significant energy [3], posing risks to health and the environment while contributing to carbon footprints. Consequently, there has been a shift toward optimizing processes to be more efficient, less wasteful, and less harmful.

The development of recoverable nano-catalysts represents a key advancement for green chemistry [4]. These tiny metal particles make separation and recovery from reactions simple, eliminating the need for energy-intensive filtration or centrifugation [5]. Moreover, their high activity enables faster, more selective reactions with enhanced precision to minimize undesired byproducts. This improves efficiency and reduces resource consumption [6].

Recoverable nano-catalysts could revolutionize pharmaceutical, petrochemical, and fine chemical industries by providing recyclable, eco-friendly alternatives to traditional catalysts [7]. Companies can significantly reduce environmental impact while maintaining or improving product quality.

This study delves deeper into recoverable nano-catalysts, exploring their synthesis, applications, and transformative possibilities for green chemistry. Their unique properties offer solutions to pressing environmental issues, and continued research promises exciting innovations in sustainable chemical production.

2. Understanding the Significance of Catalysts in the Reactions

Catalysis plays a major role across chemical, physical, and biological sciences. Approximately 85-90% of industrial processes incorporate at least one catalytic step, establishing catalysis as a foremost domain in chemistry [8]. A catalyst's primary function is to lower activation energy for reactions and, in the case of multiple possible products, to promote the formation of the most desirable product. This selectivity has become a major priority, aiming to minimize undesired byproducts even potentially at the expense of overall reaction activity.

Traditionally used in pharmaceutical and petrochemical industries, catalysts have been critical for enhancing efficiency. However, with increasing societal emphasis on sustainability, demand has grown for eco-friendly alternatives. This is where recoverable nano-catalysts come into play [9-11].

Recently, significant interest in green, sustainable chemistry has focused on designing efficient, cost-effective chemical processes. One area of focus involves using heterogeneous catalysts to prepare fine chemicals and pharmaceuticals via multicomponent reactions. However, reduced catalytic activity poses a major drawback for heterogeneous catalysts. To overcome this, it is crucial to minimize catalyst particle size. Nanostructured catalysts, also called quasi-homogeneous or soluble heterogeneous catalysts, have emerged as promising solutions to enhance activity [12]. These nano-structured catalysts bridge gaps between homogeneous and heterogeneous catalysis with their high surface area nano-scale properties. However, separating catalyst particles under 100 nm poses challenges for conventional filtration and centrifugation techniques, hindering complete catalyst recovery. To address this, magnetic nano-catalysts have gained attention due to easy separability using magnetic forces [13].

Magnetic nano-catalysts offer several advantages for organic reactions. First, they utilize inexpensive, non-toxic magnetic materials. Second, stable catalyst linkages allow environmentally friendly solvents compared to homogeneous catalysis. Third, simple external magnet separation eliminates the need for extra chemicals or additional filtration/centrifugation steps. Furthermore, magnetic nano-catalyst fabrication is generally straightforward, scalable, safe, cost-effective, and controllable. Finally, catalyst leaching is typically lower than other material-supported catalysis methods.

Magnetically recoverable nano-catalysts represent a groundbreaking chemistry advancement with effortless magnetic separation capabilities, simplifying recovery and reducing waste.

Beyond enabling reusability and associated cost/environmental benefits, magnetic properties uniquely allow controlled positioning within reactions to enhance selectivity and yields [13]. Additionally, extensive surface area and nanostructure yield heightened activity - translating to reduced reaction times, energy savings, and improved sustainability.

The potential uses of recoverable nano-catalysts are extensive, spanning chemical synthesis to addressing environmental issues. They can be employed in reactions like hydrogenation, oxidation, and carbon bond formation, providing more sustainable, eco-friendly alternatives to conventional catalysts [11]. In conclusion, understanding catalysts is key to advancing chemistry. The emergence of recoverable nano catalysts creates opportunities for more sustainable, efficient processes - promising a greener future for the chemical industry. Their versatility and green properties position them as transformative innovations that could catalyze a shift towards dramatically reduced environmental impacts across chemical production and applications.

3. Limitations of Catalysts and their Impact

Traditional catalysts have long been used in chemical reactions to accelerate processes and improve efficiency. However, these typical catalysts often have drawbacks that negatively affect the environment. One primary disadvantage of traditional catalysts is their lack of selectivity; they can promote undesirable side reactions in addition to the main reaction. This lack of control can result in the production of toxic or harmful byproducts. Separating catalysts from reaction mixtures also often requires energy-intensive techniques like filtration or distillation [14]. Separating chemicals in industry not only consumes resources but also contributes to the overall carbon footprint. Another issue is that traditional catalysts rely on non-renewable precious metals such as platinum, palladium, or rhodium [15]. Extracting these metals can harm ecosystems and local communities. Furthermore, their limited availability makes it challenging to develop scalable and sustainable production methods. However, there is hope in the form of nano catalysts. These innovative catalysts are comprised of nanoparticles that offer improved selectivity and efficiency compared to traditional methods. Best of all, they can be easily separated from the reaction mixture using a magnetic field, eliminating the need for energy-intensive separation processes. This not only reduces

waste but also allows the recycling of catalysts, minimizing resource consumption. Furthermore, magnetically recoverable nano catalysts can be designed using eco-friendly materials, reducing dependence on precious metals. This addresses sustainability concerns related to catalysts while also creating opportunities for greener and more cost-effective catalytic processes.

Through advancements in chemistry, recoverable nano catalysts can significantly reduce the environmental impact of chemical reactions. These catalysts offer several advantages, including selectivity, effortless recovery, and an environmentally sustainable design. They serve as a tool for promoting more efficient and sustainable chemical processes [16].

For years, researchers and scientists have focused on developing eco-friendly solutions in the field of green chemistry. One notable breakthrough is the introduction of nano catalysts - catalysts that operate at the nanoscale level.

Nanoparticles have a high surface area to volume ratio, enhancing their reactivity and efficiency compared to traditional catalysts. However, one challenge faced is separating and retrieving these catalysts after reactions [17].

Magnetically recoverable nano catalysts address this issue. By incorporating magnetic materials like iron oxide nanoparticles into their structure, these catalysts can be easily recovered from reaction mixtures using an external magnetic field. This eliminates the need for energy-intensive separation methods. Recoverable nano catalysts have clear advantages. First, they help minimize waste during chemical processes because the catalysts can be easily separated and reused multiple times. This significantly reduces the cost of producing fresh catalysts [18].

Second, the magnetic recoverability of these catalysts provides control over the reaction conditions. - searchers can adjust the catalysts' activity, selectivity, and even reaction speed by applying or removing a magnetic field. This level of control opens up possibilities for tuning chemical reactions and optimizing desired product yields [19].

Moreover, using recoverable nano catalysts promotes cleaner chemical processes. These catalysts can be used in flow systems where reactions occur in a controlled manner, reducing the risk of hazardous byproducts. Furthermore, recovering the catalysts lowers the chances of contamination and ensures product purity [20].

In conclusion, the introduction of recoverable nano catalysts signifies an advancement in green chemistry. Their capacity to be conveniently retrieved, reused, and controlled offers benefits in terms of sustainability, cost-effectiveness, and process safety. As scientists continue to explore and optimize these catalysts, we can expect advancements and applications across industries, revolutionizing our approach to chemical synthesis and catalysis [21].

4. Functioning Mechanism and Distinctive Characteristics of Nano-Catalysts

Magnetically retrievable nano-catalysts are at the forefront of transforming green chemistry by providing a potent solution that enhances catalytic reactions while minimizing environmental harm. These groundbreaking catalysts possess attributes that make them highly efficient and sustainable. Nano-catalysts are nanoparticles that serve as catalysts by expediting chemical reactions without being consumed. What sets magnetically retrievable nano-catalysts apart is their ability to be easily separated from reaction mixtures using an external magnetic field for recovery and reuse. This feature brings advantages in terms of both efficacy and eco-friendliness.

Typically, these nano-catalysts consist of a core material, such as iron oxide, which gives them magnetic responsiveness [22]. The surface of the nanoparticles is tailored with catalytic materials, such as metal or metal oxide nanoparticles, to facilitate the desired chemical reactions. This combination provides a way to precisely control and manipulate the behavior of the catalyst. One significant advantage of recoverable nano-catalysts is their reusability. Unlike conventional catalysts that require complex separation methods, these nano-catalysts can be easily retrieved using a magnet after the reaction and used again in subsequent reactions. This enables reducing the cost of producing fresh catalysts and minimizing waste generation (Fig. 1).

In addition, these nano-catalysts demonstrate stability and durability, ensuring sustained catalytic performance throughout multiple reaction cycles. Their small size and high surface area to volume ratio enhance their reactivity, resulting in high reaction rates and higher yields. This makes them highly efficient, enabling shorter reaction times and reduced energy consumption.

Furthermore, magnetically retrievable nano-catalysts offer versatility across various applications, including organic synthesis, pollutant degradation, and biomass conversion [9, 11, 23]. Their unique properties allow for precise control over reaction conditions and selectivity, contributing to the development of environmentally friendly and sustainable chemical processes.

The key features of magnetically recoverable nano-catalysts can be summarized as follows [24]. These innovative nano-catalysts have brought about a breakthrough in the field of green chemistry. Their ease of reuse, high efficiency, and versatility make them an invaluable tool for promoting sustainable chemical transformations. As research in this area continues to advance, we can expect to see remarkable progress and new applications that will further transform our approach to chemical synthesis and environmental sustainability.

The use of recoverable nano-catalysts can bring advancements in green chemistry and revolutionize various industries. These engineered catalysts, equipped with specialized properties, offer unique advantages and possibilities that traditional catalysts cannot match.

One industry that is greatly benefiting from the impact of recoverable nano-catalysts is pharmaceuticals [25]. These catalysts enable the efficient synthesis of drug molecules, leading to the development of new medications with improved properties. Their magnetic properties simplify catalyst separation and recov ery, thereby reducing waste and enhancing process efficiency [26].

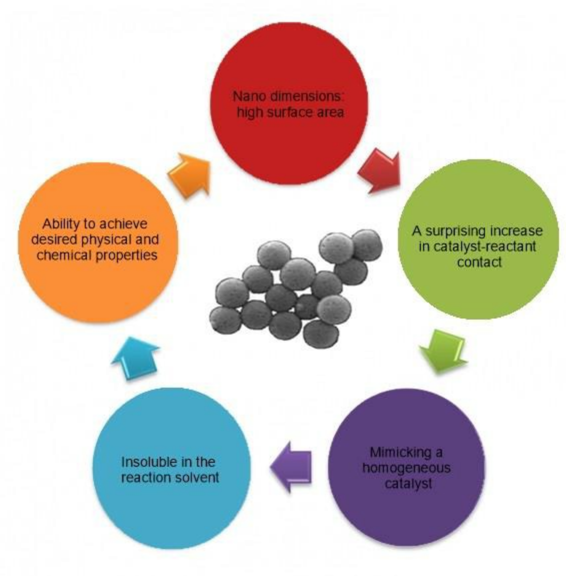

Fig. 1. Main characteristics of the nano-catalyst [24].

One industry that is greatly benefiting from the impact of recoverable nano-catalysts is pharmaceuticals [25]. These catalysts enable the efficient synthesis of drug molecules, leading to the development of new medications with improved properties. Their magnetic properties simplify catalyst separation and recovery, thereby reducing waste and enhancing process efficiency [26].

In environmental remediation, magnetically recoverable nano-catalysts are extremely valuable. They can effectively remove pollutants and contaminants from water, soil, and air in a cost-effective and eco-friendly manner [27-30].

The energy sector is another area where magnetically recoverable nano-catalysts are finding promising applications. They can be used in car converters to improve the conversion of emissions into less harmful substances [31]. Moreover, these catalysts have applications in fuel cells, enabling clean energy conversion and storage [32].

Chemical and petrochemical industries can also benefit enormously from nano-catalysts that can be recovered magnetically. These catalysts enhance the efficiency of chemical reactions, resulting in higher yields and reduced energy consumption. Additionally, their magnetic properties simplify catalyst separation and recovery, streamlining purification and recycling processes.

Furthermore, recoverable nano-catalysts have applications in the production of fine chemicals, polymers, and agricultural chemicals. Their versatility and ease of recovery make them an attractive choice to streamline industrial processes.

In conclusion, magnetically recoverable nano-catalysts have a wide range of applications across industries. They offer the potential for more sustainable chemistry by improving reaction efficiency, facilitating straightforward separation, and reducing waste. As research progresses in this exciting field, we can expect continued advancements and widespread adoption of these groundbreaking catalysts.

The use of magnetically recoverable nano-catalysts in green chemistry has brought about significant advancements in the field. These advanced nanomaterials offer a range of benefits that make them highly valuable for streamlining chemical processes.

Firstly, the magnetic properties of these nano-catalysts make separation straightforward. They can be easily recovered from reaction mixtures using a simple magnetic field, unlike conventional catalysts, which often require complex, time-consuming, and costly separation techniques that are also harmful to the environment. This not only reduces overall process time but also minimizes waste production.

Furthermore, these nano-catalysts demonstrate higher activity and selectivity compared to conventional catalysts. Their unique composition and structure provide increased surface area and better accessibility to active sites, resulting in improved reaction rates and higher product yields. This enhanced efficiency not only reduces the amount of catalyst required but also decreases energy consumption and waste generation during chemical processes.

Additionally, the magnetic recoverability allows these nano-catalysts to be reused through multiple reaction cycles. Once extracted, the catalysts can be easily redeployed in reactions, thereby reducing overall catalyst usage and waste generation.

Only this contributes to making chemical processes more sustainable. It also provides a more cost-effective solution for industrial applications. Additionally, using nano-catalysts that can be recovered magnetically allows for control over the reaction conditions. By manipulating the strength and direction of the field, we can control the movement of the catalyst within the reaction mixture, resulting in mixing and better mass transfer. This level of control over the behavior of the catalyst enables us to tune the reaction parameters, leading to optimized conditions and higher product quality.

In summary, recoverable nano-catalysts have emerged as game changers in chemistry. Their ability to be easily separated, enhanced catalytic activity, reusability, and controlled behavior make them essential tools for chemical processes. By harnessing the power of these materials, we can pave the way for a greener and more efficient future in chemistry.

5. Challenges and Potential Future Advancements in This Field

The field of recoverable nano-catalysts has shown great promise in revolutionizing green chemistry. However, like any emerging technology, some obstacles require attention and potential developments that can further enhance capabilities.

One significant challenge is scaling up production while maintaining efficiency. The production of nano-catalysts with specialized properties has been successfully achieved in lab settings. However, scaling up the process to meet industrial demands poses complex challenges. Researchers are actively working to find cost-efficient methods for large-scale synthesis that preserve catalyst quality and magnetic properties [9, 33].

Improving the activity and selectivity of these nano-catalysts is another key obstacle. Although they have demonstrated promise in facilitating chemical reactions, there is still room to enhance efficiency and specificity [34]. Researchers are exploring approaches to boost performance by tuning size, composition, and surface properties.

Additionally, reusing nano-catalysts presents difficulties. While magnetic properties enable separation from reaction mixtures, effective recovery techniques are needed to minimize any loss of activity [35]. Researchers are investigating separation methods and designing systems to facilitate nano-catalyst recovery and recycling. This not only reduces waste but also promotes sustainability.

There is tremendous potential for advancements in this emerging field. One exciting possibility is integrating nano-catalysts with technologies like microreactors or continuous flow systems. This combination can lead to improved reaction kinetics, precise control over conditions, and enhanced catalytic performance [36].

Furthermore, researchers are actively exploring the design and synthesis of multifunctional nano-catalysts that can perform tandem reactions or exhibit synergistic effects. Developing such catalysts would simplify reaction processes and create new opportunities for designing innovative and efficient chemical transformations [35].

While magnetically recoverable nano-catalysts have already made valuable contributions to green chemistry, there are still challenges to overcome and exciting prospects for future advancements.

Continuous re- search and innovation in this dynamic field can pave the way for more efficient, sustainable chemical processes, ultimately leading to a greener and more environmentally friendly future.

Real-life examples and success stories clearly showcase the transformative impact of recoverable nano catalysts in green chemistry. These groundbreaking catalysts have revolutionized the way we conduct chemical reactions by offering clear advantages over traditional catalysts.

The rapid advancement of nanotechnology has paved the way for developments across a wide range of fields, both in academia and industry. These advancements have enabled explorations into diverse applications, including targeted drug delivery [37] and water purification [38-40]. In the context of chemical research, scientists have investigated nano-catalysts for use in oil refining, petrochemical processes, polymerization reactions [41-44], and pharmaceutical reactions.

Nano-catalysts also find promising applications not just in industry but also in other sectors such as food production and textiles [45,46]. Additionally, researchers are actively investigating the use of nano-catalysts to safely convert hazardous gases via catalytic conversion [27, 31, 47, 48].

Nanotechnology has also made valuable contributions in the water and wastewater domain. Applications span from dam construction and protection of water pipelines to wastewater treatment and desalination. One major achievement is the synthesis of nanoparticles increasingly used in water treatment and environmental remediation [28-30, 49].

Nano-catalysts also play a vital role in energy production - tiny catalytic particles are added to explosives and fuels such as diesel to enhance performance. Additionally, various types of fuel cells, including proton exchange membranes, employ nano-catalysts in renewable energy systems [50]. Finally, nano-catalysts are involved in manufacturing advanced materials like carbon nanotubes and biomolecular motors [51-53].

In a recent research case study, a novel magnetic and recyclable catalyst called $Fe_3O_4@TiO_2@V_2O_5$ was synthesized and examined [54]. The effectiveness of this catalyst was investigated for the one-pot synthesis of 3,3'-diindolyl oxindole using water as a green solvent (Fig. 2). This work successfully developed an efficient and magnetically recoverable nano-catalyst for the sustainable synthesis of di-indolyl oxindoles. Key features of the technique include heterogeneous nature, thermal stability, straightforward catalyst preparation, short reaction times, high purity, simplicity, excellent yields, easy product separation/purification, eco-friendly properties, outstanding reusability without noticeable activity loss, broad substrate scope encompassing several isatins, and the use of water as a benign solvent. Additionally, this nano-catalyst can be easily recovered magnetically and reused in subsequent reactions at least five times with minimal decline in catalytic activity. The methodology provides immense benefits, including short reaction times and very high efficiency.

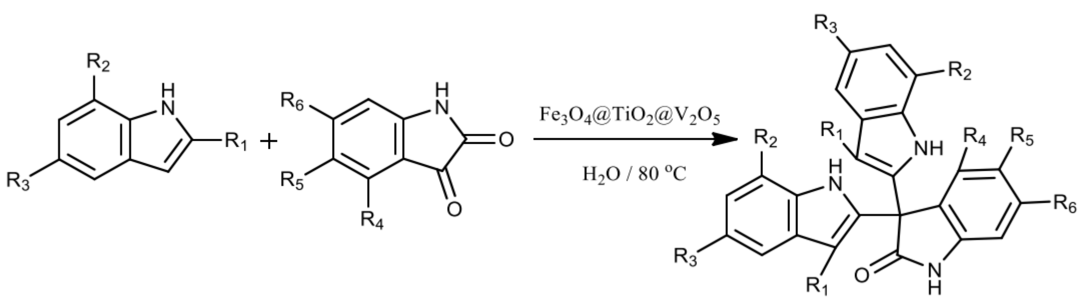

Fig. 2. Diagram illustrating the synthesis process of 3,3 diindolyloxindoles using $Fe_3O_4@TiO_2@V_2O_5$ as the catalyst [54].

6. Conclusion

In summary, the use of recoverable nano-catalysts holds immense promise for revolutionizing green chemistry. As we strive toward an environmentally sustainable future, the development and implementation of these advanced catalysts can catalyze significant positive changes across multiple industries. The ability to retrieve these nano-catalysts using external fields presents notable advantages. Firstly, it eliminates the need for complex separation techniques, thereby reducing both the time and costs associated with catalyst recovery. This paves the way for more efficient processes, ultimately improving overall productivity. Furthermore, reusing these catalysts not only promotes sustainability but also minimizes waste generation. By recovering and redeploying the nano-catalysts, we can drastically reduce the environmental impact of chemical processes. Moreover, the tailored properties of retrievable nano-catalysts enhance their activity and selectivity. This means these catalysts can drive reactions with exceptional efficiency and precision, resulting in higher yields and reduced energy consumption. Such improvements can have far-reaching implications across sectors like pharmaceuticals and renewable energy.

Ethical Considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] Ratti, R. (2020). Industrial applications of green chemistry: Status, Challenges and Prospects. *SN Applied Sciences*, 2: 1-7. https://doi.org/10.1007/s42452-020-2019-6

[2] de Marco, B. A., Rechelo, B. S., Tótoli, E. G., Kogawa, A. C., Salgado, H. R. N. (2019). Evolution of green chemistry and its multidimensional impacts: a review. *Saudi Pharmaceutical Journal*, 27(1): 1-8. https://doi.org/10.1016/j.jsps.2018.07.011

[3] Zimmerman, J. B., Anastas, P., Erythropel, H. C., Leitner, W. (2020). Designing for a green chemistry future. *Science*, 367(6476): 397-400. https://doi.org/10.1126/science.aay3060

[4] Zhang, X., Aqeel Ashraf, M., Liu, Z., Thai Pham, B., & Zhang, D. (2020). Ferrite nanoparticles (MFe_2O_4 NPs) as magnetically recoverable supports for catalysis in organic synthesis. *Synthetic Communications*, 50(18), 2735-2754. https://doi.org/10.1080/00397911.2020.1785505

[5] Gutiérrez-Serpa, A., González-Martín, R., Sajid, M., Pino, V. (2021). Greenness of magnetic nanomaterials in miniaturized extraction techniques: A review. *Talanta*, 225, 122053. https://doi.org/10.1016/j.talanta.2020.122053

[6] Mollazehi, F. (2022). Catalytic Nanoparticles and Magnetic Nanocatalysts in Organic Reactions: A Mini Review, *Main Group* Chemistry, 21(2): 697 – 708. https://doi.org/10.3233/MGC-210170

[7] Kazemi, M., Ghobadi, M. & Mirzaie, A. (2018). Cobalt ferrite nanoparticles (CoFe2O4 MNPs) as catalyst and support: magnetically recoverable nanocatalysts in organic synthesis. *Nanotechnology Reviews*, 7(1), 43-68. https://doi.org/10.1515/ntrev-2017-0138

[8] Amrutkar, R. D., Bhalerao, Sh. S., Bhoir, A. S., Bhusare, R. H., Bodhare, S. S., Borse, J. N. (2022). Role of catalyst in organic synthesis. *Current Trends in Pharmacy and Pharmaceutical Chemistry*. 4(3): 115-119. https://doi.org/10.18231/j.ctppc.2022.019

[9] Varma, R. S. (2014). Nano-catalysts with magnetic core: sustainable options for greener synthesis. *Sustainable Chemical Processes*, 2(11): 1-8. https://doi.org/10.1186/2043-7129-2-11

[10] Wang, D., Astruc, D. (2014). Magnetically Recoverable Ruthenium Catalysts in Organic Synthesis. *Molecules*, 19(4):4635-4653. https://doi.org/10.3390/molecules19044635

[11] Gawande, M. B., Rathi, A. K., Branco, P. S., Varma, R. S. (2013). Sustainable Utility of Magnetically Recyclable Nano-Catalysts in Water: Applications in Organic Synthesis. *Applied Sciences*, 3(4):656-

674. https://doi.org/10.3390/app3040656

[12] Chen, M-N., Mo, L-P., Cui, Zh-Sh., Zhang, Zh-H. (2019). Magnetic nanocatalysts: Synthesis and application in multicomponent reactions. *Current Opinion in Green and Sustainable Chemistry*. 15: 27-37. https://doi.org/10.1016/j.cogsc.2018.08.009

[13] Ziarani, G. M., Kheilkordi, Z., Mohajer, F., Badiei A., and Luque, R. (2021) Magnetically recoverable catalysts for the preparation of pyridine derivatives: an overview, *RSC Advances*, 11(28), 17456 - 17477. https://doi.org/10.1039/D1RA02418C

[14] Yu, X., Deng, J., Liu, Y., Jing, L., Hou, Z., Pei, W., Dai, H. (2022). Single-Atom Catalysts: Preparation and Applications in Environmental Catalysis. *Catalysts*, 12(10):1239. https://doi.org/10.3390/catal12101239

[15] Changmai, B., Vanlalveni, C., Ingle, A. P., Bhagat R. and Rokhum, S. L. (2020). Widely used catalysts in biodiesel production: a review, RSC Advances, 10, 41625-41679. https://doi.org/10.1039/D0RA07931F

[16] Poor Heravi, M. R., Mahjouri, D., Vessally, E. & Mohammadi B. (2023) High Catalytic Activity, Recyclable and Magnetically Separable Nanocatalyst Fe_3O_4@SiO_2-Schiff base-Pd (II) for Synthesis of 12H-Benzo [5,6] Chromeno[2,3-b] Pyridine-10-Carbonitriles and Evaluation of Antibacterial Activity. *Polycyclic Aromatic Compounds*, 44(5): 2924–2941. https://doi.org/10.1080/10406638.2023.2225681

[17] Ghobadi, M., Kargar Razi, M., Javahershenas, R. & Kazemi, M. (2021). Nanomagnetic reusable catalysts in organic synthesis. *Synthetic Communications*, 51:5, 647-669, https://doi.org/10.1080/00397911.2020.1819328

[18] Bronstein, L. M. (2015). Magnetically Recoverable Catalysts with Dendritic Ligands for Enhanced Catalysis and Easy Separation. *ChemCatChem*, 7(7), 1058–1060. https://doi.org/10.1002/cctc.201500007

[19] Rossi, L. M., Costa, N. J. S., Silva, F. P. and Wojcieszak, R. (2014). Magnetic nanomaterials in catalysis: advanced catalysts for magnetic separation and beyond. *Green Chemistry*, 16(6), 2906-2933. https://doi.org/10.1039/C4GC00164H

[20] Karimi, B., Mansouri, F. and Mirzaei, H.M. (2015). Recent Applications of Magnetically Recoverable Nanocatalysts in C-C and C-X Coupling Reactions, *Chemcatchem*. 7(12): 1736–89. https://doi.org/10.1002/cctc.201403057

[21] Alavi, F., Mamaghani, M. & Sheykhan, M. (2023) Synthesis and Application of Novel Magnetic Supported Copper Nanocatalyst for the Preparation of Thiazoles. *Polycyclic Aromatic Compounds*, 44(7): 4596-4619. https://doi.org/10.1080/10406638.2023.2254905

[22] Tokeer, A., Ruby, P. and Huma, Kh. (2019). Iron Oxide Nanoparticles: An Efficient Nano-catalyst. *Current Organic Chemistry*, 23 (9): 994-1004. https:// doi.org/10.2174/1385272823666190314153208

[23] Cheng, T., Zhang, D., Li, H., Liu, G. (2014). ChemInform Abstract: Magnetically Recoverable Nanoparticles as Efficient Catalysts for Organic Transformations in Aqueous Medium, ChemInform.Applied Organometallic Chemistry. 45(36): 259-265. https:// doi.org/10.1002/aoc.3282

[24] Polshettiwar, V., & Varma, R. S. (2010). Green chemistry by nano-catalysis. *Green Chemistry*, 12(5), 743-754. https://doi.org/10.1039/B921171C

[25] Sharma, D., Hussain, Ch. M. (2020). Smart nanomaterials in pharmaceutical analysis, *Arabian Journal of Chemistry*, 13(1): 3319-3343. https://doi.org/10.1016/j.arabjc.2018.11.007

[26] Bhatia, S. (2016). Nanoparticles types, classification, characterization, fabrication methods and drug delivery applications, Natural Polymer Drug Delivery Systems: Nanoparticles, Plants, and Algae, Springer International Publishing, Cham: 33-93. https://doi.org/10.1007/978-3-319-41129-3_2

[27] Li, J., Li, B., Sui, G., Du, L., Zhuang, Y., Zhang, Y. and Zou, Y. (2021). Removal of volatile organic compounds from air using supported ionic liquid membrane containing ultraviolet-visible light-driven

Nd- TiO_2 nanoparticles. *Journal of Molecular Structure*. 1231: 130023. https://doi.org/10.1016/j.molstruc.2021.130023

[28] Wang, B., Wu, T., Angaiah, S., Murugadoss, V., Ryu, J.E., Wujcik, E.K., Lu, N., Young, D.P., Gao, Q., and Guo, Z. (2018). Development of Nanocomposite Adsorbents for Heavy Metal Removal from Wastewater. *ES Materials and Manufacturing*. 2: 35–44. https://doi.org/10.30919/ESMM5F175

[29] Sagir, M., Tahir, M.B., Akram, J., Tahir, M.S. and Waheed, U. (2021). Nanoparticles and Significance of Photocatalytic Nanoparticles in Wastewater Treatment: A Review. *Current Analytical Chemistry*. 16(1): 38-48. https://doi.org/10.2174/1573411016999200607172553

[30] Siddeeg, S.M., Tahoon, M.A., Alsaiari, N.S., Shabbir, M., and Rebah, F.B. (2021). Application of Functionalized Nanomaterials as Effective Adsorbents for the Removal of Heavy Metals from Wastewater: A Review. *Current Analytical Chemistry*. 16(1): 1-19. https://doi.org/10.2174/1573411016999200719231712

[31] Durairajan, A., Kavitha, T., Rajendran, A., and Kumaraswamidhas, L.A. (2012). Design and manufacturing of nano-catalytic converter for pollution control in automobiles for green environment. *Indian Journal of Innovations and Developments*. 1(5): 314-319.

[32] Mashkour, M., Rahimnejad, M., Raouf, F. and Navidjouy, N. (2021). A review on the application of nanomaterials in improving microbial fuel cells. *Biofuel Research Journal*. 8(2): 1400-1416. https://doi.org/10.18331/BRJ2021.8.2.5

[33] Chen, M-N., Mo, L-P., Cui, Zh-Sh., Zhang, Zh-H. (2019). Magnetic nanocatalysts: Synthesis and application in multicomponent reactions. *Current Opinion in Green and Sustainable Chemistry*, 15: 27-37. https://doi.org/10.1016/j.cogsc.2018.08.009

[34] Chandrasekaran, S., Khandelwal, M., Fan, D., Sui, L., Chung, J.S., Misra, R.D., Yin, P., Kim, E.J., Kim, W., Vanchiappan, A., Liu, Y., Hur, S.H., Zhang, H., & Bowen, C.R. (2022). Developments and Perspectives on Robust Nano- and Microstructured Binder-Free Electrodes for Bifunctional Water Electrolysis and Beyond. *Advanced Energy Materials*, 12(23):2200409. https://doi.org/10.1002/aenm.202200409

[35] Veisi, H., Pirhayati, M., Mohammadi, P., Tamoradi, T., Hemmati, S. and Karmakar, B. (2023). Recent advances in the application of magnetic nanocatalysts in multicomponent reactions, RSC Advances, 13: 20530-20556. https://doi.org/10.1039/d3ra01208e

[36] Chadha, U., Selvaraj, S. K., Ashokan, H., Hariharan, S. P., Paul, V. M., Venkatarangan, V., Paramasivam, V. (2022). Complex Nanomaterials in Catalysis for Chemically Significant Applications: From Synthesis and Hydrocarbon Processing to Renewable Energy Applications. *Advances in Materials Science and Engineering*, Article ID 1552334, 72 pages. https://doi.org/10.1155/2022/1552334

[37] Palit, S. and Hussain, C. M. (2020). Nano-devices applications and recent advancements in nanotechnology and the global pharmaceutical industry. In: Kanchi, S., Sharma, D. (Eds.). Nanomaterials in Diagnostic Tools and Devices, Elsevier, Amsterdam, the Netherlands, pp. 395–415.

[38] Holmes, A. B., Ngan, A., Ye, J. and Gu, F. (2022). Selective photocatalytic reduction of selenate over TiO_2 in the presence of nitrate and sulfate in mine impacted water. *Chemosphere*. 287 (Pt 1): 131951. https://doi.org/10.1016/j.chemosphere.2021.131951

[39] Chang, L., Pu, Y., Jing, P., Cui, Y., Zhang, G., Xu, Sh., Cao, B., Guo, J., Chen, F., and Qiao, Ch. (2021). Magnetic core-shell $MnFe_2O_4@TiO_2$ nanoparticles decorated on reduced graphene oxide as a novel adsorbent for the removal of ciprofloxacin and Cu (II) from water. *Applied Surface Science*. 541:148400. https://doi.org/10.1016/j.apsusc.2020.148400

[40] Yaqoob, A. A., Parveen, T., Umar, K., and Mohamad Ibrahim, M. N. (2020). Role of Nanomaterials in the Treatment of Wastewater: A Review. *Water*. 12 (2): 495. https://doi.org/10.3390/w12020495

[41] Esmaeili, A. (2009). Applications of Nanotechnology in Oil and Gas Industry. Proc, AIP Conference Proceedings, PETROTECH–2009, P09–076, New Delhi, India, 11–15 January, 2-6.

[42] Mohammed, M. I., Razak, A. A. A., and Shehab, M. A. (2017). Synthesis of nano-catalyst for

hydrodesulfurization of gasoil using laboratory hydrothermal rig. *Arabian Journal for Science and Engineering*. 42 (4):1381–1387. https://doi.org/10.1007/s13369-016-2249-5

[43] Farahbod, F. and Afkhami Karaei, M. (2021). Mathematical modeling and experimental study of sulfur removal process from light and heavy crude oil in a bed occupied by ferric oxide nano-catalysts. *Environmental Technology and Innovation*, 23:101656. https://doi.org/10.1016/j.eti.2021.101656

[44] Etim, U. J., Bai, P. and Yan, Z. (2018). Nanotechnology Applications in Petroleum Refining. In: Saleh, T. A. (Ed.). Nanotechnology in Oil and Gas Industries. Springer International Publishing AG, pp.37-66.

[45] Eljeeva Emerald, F. M., Pushpadass, H. A., Joseph, D. and Jaya, S. V. (2021). Impact of Nanotechnology in Beverage Processing. In: Muthukumarappan, K., Knoerzer, K. (Eds.). Innovative Food Processing Technologies. Elsevier E-book, Amsterdam, The Netherlands, pp. 688-700.

[46] Ayatullah Hosne Asif, A. K. M., Zayedul Hasan, M. D. (2018). Application of Nanotechnology in Modern Textiles: A Review. *International Journal of Engineering & Technology Sciences*. 8 (02): 227- 231. https://doi.org/10.14741/ijcet/v.8.2.5

[47] Zhang, Y., Zhao, B., Jiang, J., Zhuo, Y. and Wang, Sh. (2016). The use of TiO2 nanoparticles to enhance CO2 absorption. *International Journal of Greenhouse Gas Control*. 50: 49-56. https://doi.org/10.1016/j.ijggc.2016.04.014

[48] Feng, X., Liu, A. and Cheng, J. (2010). Applications and development of nanotechnology in machinery industry. *Advanced Materials Research*. 121-122: 5-10. https://doi.org/10.4028/www.scientific.net/AMR.121-122.5

[49] Akhbarizadeh, R., Shayestefar, M.R. and Darezereshki, E. (2013). Competitive Removal of Metals from Wastewater by Maghemite Nanoparticles: A Comparison between Simulated Wastewater and AMD. *Mine Water and the Environment*. https://doi.org/10.1007/s10230-013- 0257-1.

[50] Mashkour, M., Rahimnejad, M., Raouf, F. and Navidjouy, N. (2021). A review on the application of nanomaterials in improving microbial fuel cells. *Biofuel Research Journal*. 8 (2): 1400-1416. https://doi.org/10.18331/BRJ2021.8.2.5

[51] Kouzu, M., Kasuno, T. and Tajika, M., (2008). Active phase of calcium oxide used as solid base catalyst or transesterification of soybean oil with refluxing methanol, *Journal of Applied Catalyst*, 334(1): 357-365. https://doi.org/10.1016/j.apcata.2007.10.023

[52] Saththasivam, J., Yiming, W., Wang, K., Jin, J. and Liu, Z. (2018). A Novel Architecture for Carbon Nanotube Membranes towards Fast and Efficient Oil/water Separation. Scientific Reports. 8(1): 7418. https://doi.org/ 10.1038/s41598-018-25788-9

[53] Mustapha, M. H., Azizi, A. K., Aini, W. N., Mokhtar, W. and Mohamed, A. M. (2021). Application of Nanoparticles for the Enhanced Production of Biodiesel. In: Editor(s): Inamuddin, Ahamed, M. I., Boddula, R., Rezakazemi, M. (Eds). Biodiesel Technology and Applications. Scrivener Publishing LLC, pp. 465-480.

[54] Hassani, H., and Agah, A. (2021). Fe_3O_4@TiO_2@V_2O_5 as an Efficient Magnetic Nanoparticle for Synthesis of Di-Indolyl Oxindole Derivatives. Journal of Mining and Environment, 12(4), 1041-1053. https://doi.org/10.22044/jme.2021.11092.2086